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Detecting sterile dark matter in space

Alexander Kusenko

*Department of Physics and Astronomy,
University of California, Los Angeles, CA 90095-1547, USA*

Space-based instruments provide new and, in some cases, unique opportunities to search for dark matter. In particular, if dark matter comprises sterile neutrinos, the x ray detection of their decay line is the most promising strategy for discovery. Sterile neutrinos with masses in the keV range could solve several long-standing astrophysical puzzles, from supernova asymmetries and the pulsar kicks to star formation, reionization, and baryogenesis. The best current limits on sterile neutrinos come from Chandra and XMM-Newton. Future advances can be achieved with a high-resolution x-ray spectrometry in space.

Keywords: dark matter, sterile neutrinos, x-ray astronomy

1. Introduction

There is an overwhelming amount of evidence that most of the matter in the universe is not made of ordinary atoms, but, rather, of new, yet undiscovered particles¹. The evidence for dark matter is based on several independent observations, including cosmic microwave background radiation, gravitational lensing, the galactic rotation curves, and the x-ray observations of clusters. None of the Standard Model particles can be dark matter. Hence, the identification of dark matter will be a discovery of new physics beyond the Standard Model.

To detect dark matter one must guess its properties, which ultimately determine one's strategy for detection. One can base one's guesses on compelling theoretical ideas or on some observational clues.

One of the most popular theories for physics beyond the Standard Model is supersymmetry. A class of supersymmetric extensions of the Standard Model predict dark matter in the form of either the lightest supersymmetric particles², or SUSY Q-balls³. Another theoretically appealing possibility is dark matter in the form of axions⁴. Axion is a very weakly interacting field which accompanies the Peccei–Quinn solution of the strong CP problem. There are several other dark-matter candidates that are well motivated by theoretical reasoning. A comprehensive review of possibilities is not our purpose; rather, we will focus on the forms of dark matter which are well-motivated and for which there are new opportunities in space research.

Right-handed or sterile neutrinos can be the dark matter^{5–8}. The existence of

such right-handed states is implied by the discovery of the active neutrino masses. Although it is not impossible to explain the neutrino masses otherwise, most models introduce gauge singlet fermions that give the neutrinos their masses via mixing. If one of these right-handed states has mass in the $\sim 1 - 50$ keV range, it can be the dark matter. Several indirect astrophysical clues support this hypothesis. Indeed, if the sterile neutrinos exist, they can explain the long-standing puzzle of pulsar velocities⁹. In addition, the x rays produced in decays of the relic neutrinos could increase the ionization of the primordial gas and can catalyze the formation of molecular hydrogen at redshift as high as 100. Since the molecular hydrogen is an important cooling agent, its increased abundance could cause the early and prompt start formation^{10,11}. Sterile neutrinos can also help the formation of supermassive black holes in the early universe¹³. For smaller masses, the sterile neutrinos have a long enough free-streaming length to rectify several reported inconsistencies between the predictions of cold dark matter on small scales and the observations. The consensus of these indirect observational hints helps make a stronger case for the sterile dark matter.

2. Sterile neutrinos

The number of light “active” left-handed neutrinos – three – is well established from the LEP measurements of the Z-boson decay width. In the Standard Model, the three active neutrinos fit into the three generations of fermions. In its original form the Standard Model described massless neutrinos. The relatively recent but long-anticipated discovery of the neutrino masses has made a strong case for considering right-handed neutrinos, which are $SU(3) \times SU(2) \times U(1)$ singlets. The number of right-handed neutrinos may vary and need not equal to three.¹⁴ Depending on the structure of the neutrino mass matrix, one can end up with none, one, or several states that are light and (mostly) sterile, *i.e.*, they interact only through their small mixing with the active neutrinos.

Sterile neutrino is not a new idea. The name “sterile” was coined by Bruno Pontecorvo in 1967¹⁵. Many seesaw models¹⁶ assume that sterile neutrinos have very large masses, which makes them unobservable. However, one can consider a lighter sterile neutrino, which can be dark matter⁵. Emission of sterile neutrinos from a supernova could explain the pulsar kicks if the sterile neutrino mass was several keV^{17,18}. More recently, a number of papers have focused on this range of masses because several indirect observational hints suggest the existence of a sterile neutrino with such a mass.

Unless some neutrino experiments are wrong, the present data on neutrino oscillations cannot be explained with only the active neutrinos. Neutrino oscillation experiments measure the differences between the squares of neutrino masses, and the results are: one mass squared difference is of the order of $10^{-5}(\text{eV}^2)$, the other one is $10^{-3}(\text{eV}^2)$, and the third is about $1(\text{eV}^2)$. Obviously, one needs more than three masses to get the three different mass splittings which do not add up to zero.

Since we know that there are only three active neutrinos, the fourth neutrino must be sterile. However, if the light sterile neutrinos exist, there is no compelling reason why their number should be limited to one.

The neutrino masses can be introduced into the Standard Model by means of the following addition to the lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{\nu}_{s,a} (i\partial_\mu \gamma^\mu) \nu_{s,a} - y_{\alpha a} H \bar{L}_\alpha \nu_{s,a} - \frac{M_{aa}}{2} \bar{\nu}_{s,a}^c \nu_{s,a} + h.c., \quad (1)$$

where H is the Higgs boson and L_α ($\alpha = e, \mu, \tau$) are the lepton doublets, while $\nu_{s,a}$ ($a = 1, \dots, N$) are the additional singlets. This model, dubbed νMSM ⁸, provides a natural framework for considering sterile neutrinos. Of course, the gauge singlet fields may have some additional couplings omitted from eq. (1). The neutrino mass matrix has the form

$$M = \begin{pmatrix} \tilde{m}_{3 \times 3} & D_{3 \times N} \\ D_{N \times 3}^T & M_{N \times N} \end{pmatrix}, \quad (2)$$

where the Dirac masses $D_{\alpha a} = y_{\alpha a} \langle H \rangle$ are the result of spontaneous symmetry breaking. For symmetry reasons one usually sets $\tilde{m}_{3 \times 3}$ to zero. As for the right-handed Majorana masses M , the scale of these masses can be either much greater or much smaller than the electroweak scale.

The seesaw mechanism¹⁶ can explain the smallness of neutrino masses in the presence of the Yukawa couplings of order one. For this purpose, one assumes that the Majorana masses are much larger than the electroweak scale, and the smaller eigenvalues of the mass matrix (2) are suppressed by the ratio of $\langle H \rangle$ to M .

However, the origin of the Yukawa couplings remains unknown, and, in the absence of the fundamental theory, there is no compelling reason to believe that these couplings must be of order 1. Indeed, the Yukawa couplings of most known fermions are much smaller than one, e.g. the Yukawa coupling of the electron is $\sim 10^{-6}$.

Thus, for all we know, the scale of the Majorana mass M in eq. (2) can be much smaller than the electroweak scale. If $M \sim 1$ eV, the sterile neutrinos with the mass $m_s \sim 1$ eV can explain the LSND results¹⁹. If $M \sim 1$ keV, the sterile neutrinos with the corresponding mass could explain the pulsar kicks^{17,18} and dark matter⁵, and they can also play a role in generating the matter-antimatter asymmetry of the universe¹².

3. Production of sterile neutrinos in the early universe

Sterile neutrinos can be produced in the early universe from neutrino oscillations, as well as from other couplings, not included in eq. (1). For example, dark matter in the form of sterile neutrinos can be produced by a direct coupling to the inflaton²⁰.

At very high temperatures the active neutrinos have frequent interactions in plasma, which reduce the probability of their conversions into sterile neutrinos²¹. The mixing of sterile neutrinos with one of the active species in plasma can be

represented by an effective, density and temperature dependent mixing angle^{5–7}:

$$|\nu_1\rangle = \cos\theta_m |\nu_e\rangle - \sin\theta_m |\nu_s\rangle \quad (3)$$

$$|\nu_2\rangle = \sin\theta_m |\nu_e\rangle + \cos\theta_m |\nu_s\rangle, \quad (4)$$

where

$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V_m - V_T)^2}. \quad (5)$$

Here V_m and V_T are the effective matter and temperature potentials. In the limit of small angles and small lepton asymmetry, the mixing angle can be approximated as

$$\sin 2\theta_m \approx \frac{\sin 2\theta}{1 + 0.27\zeta \left(\frac{T}{100 \text{ MeV}}\right)^6 \left(\frac{\text{keV}^2}{\Delta m^2}\right)} \quad (6)$$

where $\zeta = 1.0$ for mixing with the electron neutrino and $\zeta = 0.30$ for ν_μ and ν_τ .

Obviously, thermal effects suppress the mixing significantly for temperatures $T > 150 (m/\text{keV})^{1/3} \text{ MeV}$. If the singlet neutrinos interact only through mixing, all the interaction rates are suppressed by the square of the mixing angle, $\sin^2 \theta_m$. It is easy to see that these sterile neutrinos are *never* in thermal equilibrium in the early universe. Thus, in contrast with the case of the active neutrinos, the relic population of sterile neutrinos is not a result of a freeze-out. One immediate consequence of this observation is that the Gershtein–Zeldovich bound²² and the Lee–Weinberg bound²³ do not apply to sterile neutrinos. In general, the existing experimental constraints on sterile neutrinos²⁴ allow a wide range of parameters, especially for small mixing angles.

One can calculate the production of sterile neutrinos in plasma by solving the Boltzmann equation for the distribution function $f(p, t)$:

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_s(p, t) \equiv xH\partial_x f_s = \quad (7)$$

$$\Gamma_{(\nu_a \rightarrow \nu_s)} (f_a(p, t) - f_s(p, t)), \quad (8)$$

where H is the Hubble constant, $x = 1 \text{ MeV } a(t)$, $a(t)$ is the scale²⁵ factor, and Γ is the probability of conversion. The solution^{5–7,25} is shown in Fig.1 as "dark matter produced via mixing". One should keep in mind that this solution is subject to hadronic uncertainties²⁶.

If the sterile neutrinos have additional interactions, not included in eq. (1), the relic population of these particles can be produced via different mechanisms. One example is a direct coupling of sterile neutrinos to the inflaton²⁰. In this case the production of sterile neutrinos may not be governed by the mixing angle, although the mixing angle still controls the decay rate and, therefore, some of the constraints discussed below depend on the mixing angles.

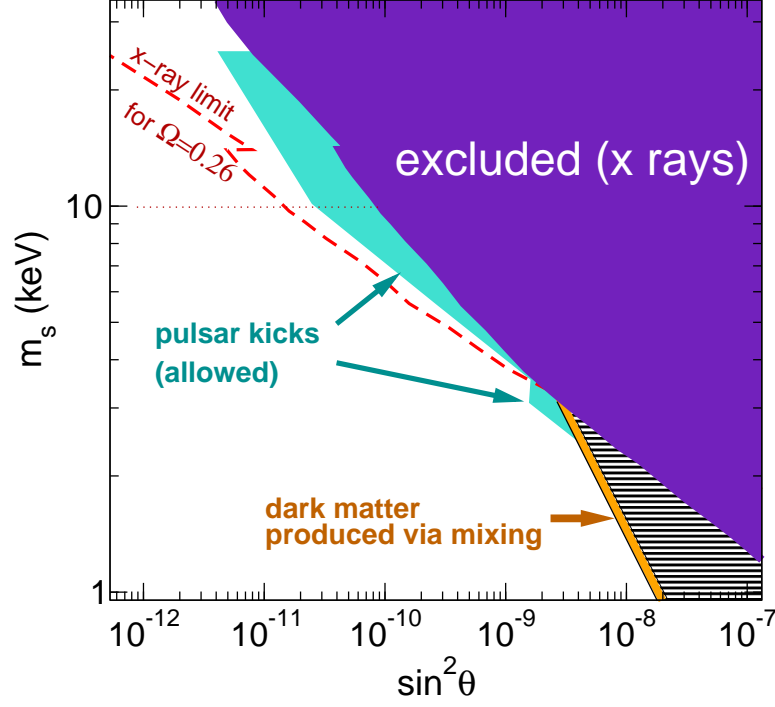


Fig. 1. The range of the sterile neutrino masses and mixing angles. The x-ray limits depend on the abundance of the relic sterile neutrinos, which, in turn, depends on their production mechanism. If the sterile neutrinos are produced only via their mixing with active neutrinos, they can be dark matter for masses below 3 keV, as shown in the figure. This range is in conflict with the 10 keV lower bound from the Lyman-alpha forest shown by a dotted line. In sharp contrast, the observations of dwarf spheroidal galaxies favor the masses of a few keV. If the sterile neutrinos are produced via some additional couplings, besides the mixing with the active neutrinos, and if the sterile neutrinos make up all the dark matter ($\Omega = 0.26$), the corresponding x-ray limit is shown as a dashed line. Also shown is the allowed range of parameters consistent with the pulsar kicks.

4. Constraints on sterile dark matter

Although dark-matter sterile neutrinos are stable on cosmological time scales, they nevertheless decay^{7,27}. The dominant decay mode, into three light neutrinos, is "invisible" because the daughter neutrinos are beyond the detection capabilities of today's experiments. The most prominent "visible" mode is decay into one active neutrino and one photon, $\nu_s \rightarrow \nu_a \gamma$. Assuming the two-neutrino mixing for simplicity, one can express the inverse width of such a decay as²⁸

$$\tau \equiv \Gamma_{\nu_s \rightarrow \nu_a \gamma}^{-1} = 1 \times 10^{26} \text{s} \left(\frac{7 \text{ keV}}{m_s} \right)^5 \left(\frac{1 \times 10^{-9}}{\sin^2 \theta} \right), \quad (9)$$

where m_s is the mass and θ is the mixing angle.

Since this is a two-body decay, the photon energy is half the mass of the sterile neutrino. The monochromatic line from dark matter decays can, in principle, be

observed by x-ray telescopes. No such observation has been reported, and some important limits have been derived on the allowed masses and mixing angles. These constraints are based on different astrophysical objects, from Virgo and Coma clusters, to Large Magellanic Clouds, to Milky Way halo and its components²⁷. There are different uncertainties in modeling the dark matter populations in these objects. Different groups have also used very different methods in deriving these bounds: from a conservative assumption that the dark-matter line should not exceed the signal, to more ambitious approaches that involved modeling the signal or merely fitting it with a smooth curve and requiring that the line-shaped addition not affect the quality of the fit. In any case, the limits apply to the flux of x rays, which can be translated into the limits on mass and mixing angle if the sterile neutrino abundance is known. As we discussed above, the production is possible via the mixing alone, but some additional couplings and other production mechanisms are by no means excluded²⁰. Most published bounds²⁷ *assume* that sterile neutrinos make up all the dark matter, that is $\Omega_s = 0.26$. The limit based on this assumption is shown as a dashed (red) line in Fig. 1. However, it should not be used as the exclusion limit for sterile neutrinos in general, because it is possible that $\Omega_s < 0.26$, while the sterile neutrinos could still explain the pulsar velocities and they could play a role in the star formation.

A different kind of limit based on the same x-ray data²⁷ can be set without assuming $\Omega_s = 0.26$. As long as there is a mixing due to the couplings in the lagrangian (1), some sterile neutrinos are produced in the hot plasma, regardless of any additional couplings that may or may not be present. This amount corresponds to the lower bound on the sterile neutrino abundance, and the bound obtained this way is the most robust, model-independent limit. The corresponding exclusion region is shown in Fig. 1.

Additional constraints on dark matter come from the observations of the Lyman-alpha forest^{29–31}, which limit the sterile neutrino mass from below. Based on the high-redshift data from SDSS and some modeling of gas dynamics, one can set a limit as strong as 14 keV³⁰. However, the high-redshift data may have systematic errors, and more conservative approaches, based on the relatively low-redshift data, have led to some less stringent bounds²⁹. Recently Viel et al.³¹ have reanalyzed the high-redshift data and arrived at the bound $m_s > 10$ keV. The mass bounds as quoted depend on the production mechanism in the early universe.

The Lyman-alpha observations constrain the free-streaming lengths of dark matter particles, not their masses. For each cosmological production mechanism, the relation between the free-streaming length and the mass is different³². For example, the bound $m_s > 10$ keV³¹ applies to the production model due to Dodelson and Widrow⁵. If the lepton asymmetry of the universe (which is unknown *a priori*) is sufficiently large, then the sterile neutrinos can be produced through resonant Mikheev-Smirnov-Wolfenstein³³ (MSW) oscillations in the early universe³⁴. These neutrinos are non-thermal and colder because the adiabaticity condition selects the low-energy part of the neutrino spectrum. Even within a given cosmological sce-

nario, there are uncertainties in the production rates of neutrinos for any given mass and mixing angle²⁶. These uncertainties may further affect the interpretation of the Lyman-alpha bounds in terms of the sterile neutrino mass.

It should also be mentioned that the Lyman-alpha bounds appear to contradict the observations of dwarf spheroidal galaxies³⁶, which suggest that dark matter is warm and which would favor the 1–5 keV mass range for sterile neutrinos. There are several inconsistencies between the predictions of N-body simulations of cold dark matter (CDM) and the observations³⁵. Each of these problems may find a separate independent solution. Perhaps, a better understanding of CDM on small scales will resolve these discrepancies. It is true, however, that warm dark matter in the form of sterile neutrinos is free from all these small-scale problems altogether, while on large scales WDM fits the data as well as CDM.

If the sterile neutrinos make up only a part of dark matter, the Lyman-alpha bounds do not apply. In this case, the sterile neutrinos may still be responsible for pulsar velocities, and they can play a role in star formation and reionization of the universe. Also, if inflation ended with a low reheat temperature, the bounds are significantly weaker³⁷.

5. Reionization and star formation

Sterile neutrinos decay in the early universe, in particular, during the "dark ages" following recombination. The ionizing photons are too few to affect the cosmic microwave background directly³⁸, but they can have an important effect on star formation and reionization. The star formation requires cooling and collapse of gas clouds, which is impossible unless the fraction of molecular hydrogen is high enough³⁹. Star formation is accompanied by the reionization of gas in the universe. The WMAP (three years) measurement⁴⁰ of the reionization redshift $z_r = 10.9^{+2.7}_{-2.3}$ has posed a new challenge to theories of star formation. On the one hand, stars have to form early enough to reionize gas at redshift 11. On the other hand, the spectra of bright distant quasars imply that reionization must be completed by redshift 6. Stars form in clouds of hydrogen, which collapse at different times, depending on their sizes: the small clouds collapse first, while the large ones collapse last. If the big clouds must collapse by redshift 6, then the small halos must undergo the collapse at an earlier time. It appears that the star formation in these small halos would have occurred at high redshift, when the gas density was very high, and it would have resulted in an unacceptable overproduction of the Thompson optical depth⁴¹. To be consistent with WMAP, the efficiency for the production of ionizing photons in minihalos must have been at least an order of magnitude lower than expected⁴¹. One solution is to suppress the star formation rate in small halos by some dynamical feedback mechanism. The suppression required is by at least an order of magnitude.

An alternative solution is to consider warm dark matter, in which case the small clouds are absent altogether. However, it has been argued that "generic" warm dark matter can delay the collapse of gas clouds⁴². This problem does not arise in the

case of sterile neutrinos, because the x-ray photons from their slow decays could have increased the production of molecular hydrogen and could have precipitated a rapid and prompt star formation at a high enough redshift^{10,11}.

6. Pulsar velocities

The space velocities of pulsars range from 250 km/s to 500 km/s.^{43–44} Some 15% of pulsars⁴⁴ appear to have velocities greater than 1000 km/s, while the fastest pulsars have speeds as high as 1600 km/s. The origin of these velocities remains a puzzle⁹. Since most of the supernova energy, as much as 99% of the total 10^{53} erg are emitted in neutrinos, a few per cent anisotropy in the distribution of these neutrinos would be sufficient to explain the pulsar kicks.

Neutrinos are always *produced* with an asymmetry, but they usually *escape* isotropically. The asymmetry in production comes from the asymmetry in the basic weak interactions in the presence of a strong magnetic field^a. Indeed, if the electrons and other fermions are polarized by the magnetic field, the cross section of the urca processes, such as $n + e^+ \rightleftharpoons p + \bar{\nu}_e$ and $p + e^- \rightleftharpoons n + \nu_e$, depends on the orientation of the neutrino momentum:

$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu) \quad (10)$$

Depending on the fraction of the electrons in the lowest Landau level, this asymmetry can be as large as 30%, which is, seemingly, more than one needs to explain the pulsar kicks.⁴⁶ However, this asymmetry is completely washed out by scattering of neutrinos on their way out of the star.⁴⁷ This is intuitively clear because, as a result of scatterings, the neutrino momentum is transferred to and shared by the neutrons. In the approximate thermal equilibrium, no asymmetry in the production or scattering amplitudes can result in a macroscopic momentum anisotropy. This statement can be proved rigorously⁴⁷.

However, if the neutron star cooling produced a particle whose interactions with nuclear matter were *even weaker* than those of ordinary neutrinos, such a particle could escape the star with an anisotropy equal its production anisotropy. The sterile neutrinos, whose interactions are suppressed by $(\sin^2 \theta_m)$ can play such a role^{17,18,48}. The region of masses and mixing angles consistent with this explanation for the pulsar kicks is shown in Fig. 1. The neutrino-driven kicks have a number of ramifications: in particular, they can increase the energy of the shock and can generate asymmetric jets, the strongest of which is aligned with the direction of the pulsar motion⁴⁹.

^aHere we disregard the neutrino magnetic moments, which are negligible in the Standard Model and its simplest extensions. Even for vanishing magnetic moments, neutrino oscillations are affected by the magnetic field through the polarization of the matter fermions⁴⁵

7. Conclusion

Several independent observational hints point to sterile neutrinos with masses in the keV range. Pulsar velocities can be explained by the emission of such sterile neutrinos from a supernova, because the sterile neutrino emission is anisotropic in the presence of the magnetic field. The x-ray photons from the decays of the sterile neutrinos can ionize the primordial gas and can cause an increase in the fraction of molecular hydrogen, which makes a prompt star formation possible at a relatively high redshift. The sterile neutrinos can be the dark matter. In addition, they could have played a role in generating the matter-antimatter asymmetry of the universe. Future observations of x-ray telescopes may be able to discover the relic sterile neutrinos by detecting keV photons from their decays.

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